U.S. GODAE: Global Ocean Prediction with the Hybrid Coordinate Ocean Model (HYCOM)

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LONG-TERM GOALS

A broad partnership of institutions is collaborating in developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). These systems will be transitioned for operational use by the U.S. Navy at both the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, CA, and by NOAA at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The systems will run efficiently on a variety of massively parallel computers and will include sophisticated, but relatively inexpensive, data assimilation techniques for assimilation of satellite altimeter sea surface height (SSH) and sea surface temperature (SST) as well as in-situ temperature, salinity, and float displacement.

The Partnership under this proposal represents a truly broad spectrum of the oceanographic community, bringing together academia, federal agencies, and industry/commercial entities, spanning modeling, data assimilation, data management and serving, observational capabilities, and application of HYCOM prediction system outputs. The institutions participating in this Partnership have long histories of supporting and carrying out a wide range of oceanographic and ocean prediction-related research and data management. All institutions are committed to validating an operational hybrid-coordinate ocean model that combines the strengths of the vertical coordinates used in the present generation of ocean models by placing them where they perform best. This collaborative Partnership provides an opportunity to leverage and accelerate the efforts of existing and planned projects, in order to produce a higher quality product that will collectively better serve a wider range of users than would the individual projects. In addition to operational eddy-resolving global and basin-scale ocean prediction systems for the U.S. Navy and NOAA, respectively, this project offers an outstanding opportunity for NOAA-Navy collaboration and cooperation ranging from research to the operational level.

This effort is part of a 5-year (FY04-08) multi-institutional National Ocean Partnership Program (NOPP) project which includes the U. of Miami (E. Chassignet, G. Halliwell, M. Iskandarani, T. Chin, A. Mariano, Z. Garraffo, A. Srinivasan), NRL/STENNIS (H. Hurlburt, A. Wallcraft, J. Metzger, B. Kara, J. Cummings, G. Jacobs, H. Ngodock, L. Parent, C.A. Blain, P. Hogan, J. Kindle), NAVOCEANO (E. Johnson, J. Harding), FNMOC (M. Clancy), NRL/MONTEREY (R. Hodur, M. Flatau, X. Hong, J. Pullen), NOAA/NCEP/MMAB (D.B. Rao, C. Lozano), NOAA/NOS (F. Aikman), NOAA/AOML (C. Thacker), NOAA/PMEL (S. Hankin), Planning System Inc. (O.M. Smedstad, B. Lunde), NASA-GISS (R. Bleck), SHOM (R. Baraille), LEGI (P. Brasseur), OPeNDAP (P. Cornillon),

U. of S. Mississippi (W. Schmitz), U. of N. Carolina (C. Werner), Rutgers (J. Wilkin, D. Haidvogel), U. of S. Florida (R. Weisberg), Fugro-GEOS/Ocean Numerics (D. Szabo, R. Stephens), Horizon Marine Inc. (J. Feeney, S. Anderson), ROFFS (M. Roffer), Orbimage (L. Stathoplos), Shell Oil Company (M. Vogel), ExxonMobil (O. Esenkov).

OBJECTIVES

The Partnership is addressing the Global Ocean Data Assimilation Experiment (GODAE) objectives of three-dimensional (3D) depiction of the ocean state at fine resolution in real-time and provision of boundary conditions for coastal and regional models. It will also provide the ocean component and oceanic boundary conditions for a global coupled ocean-atmosphere prediction model. It will make these results available to the GODAE modeling community and general users on a 24/7 operational basis via a comprehensive data management strategy.

APPROACH AND WORK PLAN

HYCOM development is the result of collaborative efforts among the University of Miami, the Naval Research Laboratory (NRL), and the Los Alamos National Laboratory (LANL), as part of the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling. This effort was funded by the National Ocean Partnership Program (NOPP) in 1999 to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004). HYCOM has been configured globally, on basin scales, and regionally at 1/12º (~7 km mid-latitude) resolution. More details of these free-running simulations can be found at http://hycom.rsmas.miami.edu and in the ONR report by H. Hurlburt.

While HYCOM is a sophisticated model, including a large suite of physical processes and incorporating numerical techniques that are optimal for dynamically different regions of the ocean, data assimilation is still essential for ocean prediction a) because many ocean phenomena are due to flow instabilities and thus are not a deterministic response to atmospheric forcing, b) because of errors in the atmospheric forcing, and c) because of ocean model imperfections, including limitations in resolution. One large body of data is obtained remotely from instruments aboard satellites. They provide substantial information about the ocean's space-time variability at the surface, but they are insufficient by themselves for specifying the subsurface variability. Another significant body of data is in the form of vertical profiles from XBTs, CTDs, and profiling floats *(e.g.,* ARGO). Even together, these data sets are insufficient to determine the state of the ocean completely, so it is necessary to exploit prior knowledge in the form of statistics determined from past observations as well as our understanding of ocean dynamics. Our plan is to combine all sources of information synergistically to produce the best possible depiction of the evolving ocean. Several techniques for assimilating data into HYCOM are either in place or under development. These techniques vary in sophistication and computational requirements and include: Optimum Interpolation (OI/Cooper-Haines) (PSI, O.M. Smedstad; SHOM, R. Baraille), MVOI/3D-VAR (NRL, J. Cummings; NOAA/NCEP, C. Lozano), SEEK filter (Sverdrup Inc., L. Parent; LEGI, P. Brasseur), Reduced Order Information Filter (ROIF) (U. of Miami, T. Chin, A. Mariano; NOAA/AOML, C. Thacker), Ensemble Kalman Filter (EnKF) (NRL, H. Ngodock; Ocean Numerics, L. Bertino), Reduced Order Adaptive Filter (ROAF) (including adjoint) (SHOM, R. Baraille), and the 4D-VAR Representer Method (NRL, H. Ngodock, G. Jacobs). All of these techniques are available for this project and all developers are part of this Partnership.

In order to increase the predictability of coastal regimes, several partners within the HYCOM consortium are developing and evaluating boundary conditions for coastal prediction models based on the HYCOM data assimilative system outputs. The inner nested models may or may not be HYCOM, so the coupling of the global and coastal models needs to be able to handle unlike vertical grids. Coupling HYCOM to HYCOM is now routine via one-way nesting (Zamudio et al., 2006). Coupling HYCOM to other models, such as the Navy Coastal Ocean Model (NCOM) or the Regional Ocean Model System (ROMS), has already been demonstrated, while coupling of HYCOM to unstructured grid/finite element models is in progress.

RESULTS

Funding was received for the U. of Miami and for PSI, USF, UNC, OPeNDAP, Fugro-GEOS, Rutgers, and W. Schmitz via U. of Miami subcontracts. We report here on some of the progress made during FY 05.

a) **Ocean forecasting systems**

For the present Navy near real-time 1/12^{o} North Atlantic HYCOM ocean forecasting system (the global configuration is scheduled to become operational in 2007), real time satellite altimeter data (Geosat-Follow-On (GFO), ENVISAT, and Jason-1) are provided via the Altimeter Data Fusion Center (ADFC) at NAVOCEANO to generate the two-dimensional Modular Ocean Data Assimilation System (MODAS) SSH analysis (Fox et al., 2002) that is assimilated daily. Before one can assimilate the SSH anomalies determined from the satellite altimeter data, it is necessary to know the oceanic mean SSH over the time period of the altimeter observations. Unfortunately, the geoid is not presently known accurately on the mesoscale. Several satellite missions are either underway or planned to try to determine a more accurate geoid, but until the measurements become accurate to within a few centimeters on scales down to approximately 30 km, one has to define a mean oceanic SSH. At the scales of interest (tens of kilometres), it is necessary to have the mean of major ocean currents and associated SSH fronts sharply defined. This is not feasible from coarse hydrographic climatologies (~1^{o} horizontal resolution) and the approach taken by the HYCOM data assimilative system has been to use a model-derived mean SSH. This requires a fully eddy-resolving ocean model which is consistent with hydrographic climatologies and with fronts in the correct position. The HYCOM-based system uses the model mean generated by a previous 1/12^{o} North Atlantic simulation performed with MICOM (see Chassignet and Garraffo (2001) for a discussion). The model sea surface temperature is relaxed to the daily MODAS SST analysis which uses daily Multi-Channel Sea Surface Temperature (MCSST) data derived from the 5-channel Advanced Very High Resolution Radiometers (AVHRR) – globally at 8.8 km resolution and at 2 km in selected regions. For an evaluation of the North Atlantic system, the reader is referred to Chassignet et al. (2005, 2006).

The Navy North Atlantic system runs once a week every Wednesday and consists of a 10-day hindcast and a 14-day forecast. The atmospheric forcing for the 14-day forecasts gradually reverts toward climatology after five days. The last forecast record is weighted with the contemporaneous climatological values over a ten day time span. Over that time, a linearly decreasing (increasing) weight (1-weight) is used for the forecast (climatology). During the forecast period, the SST is relaxed toward climatologically-corrected persistence of the nowcast SST with a relaxation time scale of 1/4 the forecast length (i.e., 1 day for a 4-day forecast). The near real-time North Atlantic basin model outputs are made available to the community at large within 24 hours via the Miami Live Access

Server (LAS) (http://hycom.rsmas.miami.edu/las). Specifically, the LAS supports model-data and model-model comparisons; provides HYCOM subsets to coastal or regional nowcast/forecast partners as boundary conditions, and increases the usability of HYCOM results by "application providers".

The NRL Coupled Ocean Data Assimilation (NCODA) system is being implemented in HYCOM. The NCODA analysis was initially designed to perform in z-space and it was decided that, as an interim solution, NCODA would be implemented by interpolating the HYCOM vertical coordinate to z-space, perform the NCODA analysis, and then convert back to the HYCOM vertical coordinate. The thought was that this would be the simplest (fastest) way to implement NCODA in HYCOM. Several problems have been encountered during this process. One problem has been how to update the HYCOM variables in a dynamically consistent way. The output from NCODA consists of analyzed fields and increments of T, S U, and V. One approach has been to update the temperature and salinity (and calculate the new density) and then let the hybrid generator take care of moving the interfaces. The T and S increments from NCODA can be large if the model first guess is far from the observations. This approach turned out to produce collapsed layers and excessive diapycnal mixing. The conclusion is that the NCODA analysis needs to be performed on the HYCOM native vertical grid. Work has also started in cooperation with L. Parent to check the implementation of NCODA in a sigma-z version of HYCOM. The idea is to make sure that NCODA works smoothly with HYCOM when configured with a vertical coordinate that NCODA has already been tested with (i.e., NCOM, POP).

Work was also started on the implementation of the ensemble Kalman filter. This work is in cooperation with H. Ngodock now at NRL. The 1/12º Gulf of Mexico version of HYCOM has been used in this implementation. The ensemble calculations are set up so that the number of ensemble members can be controlled by the model script. The standard HYCOM code is used to integrate the individual members. The total ensemble that is used in the analysis is put together from the standard output files from HYCOM. The framework for the implementation is in place, including the calculation of perturbed forcing fields to be used by the different ensemble members. The cooperation with L. Bertino and his team at the Nansen Center is an important part of the ensemble Kalman filter implementation. A. Srinivasan and M. Chin are also using the same Gulf of Mexico configuration to evaluate the ROIF.

In preparation for the data assimilation experiment with NCODA and the 1/12º Pacific Ocean HYCOM, the mean SSH over the time period, 1994-2003, has been checked for consistency with available observation. The rubber sheeting software used to produce an updated mean SSH field for NLOM has been modified so that it works with a HYCOM mean field. An eddy in the mean SSH field located north of the Kuroshio at about 40ºN and 145ºE, has been removed using the rubber sheeting technique.

Once we have a working system coupling NCODA and HYCOM, the 1/12º Pacific model will be set up with the NCODA assimilation and a multi-year experiment will be performed. This work will be performed by O.M. Smedstad in collaboration with J. Metzger. The new 1/12º North Atlantic σ_2^* configuration will also be run with NCODA and the performance of this experiment will be compared to the results from the present near real-time Atlantic system. The 1/12º global version of HYCOM will then be evaluated with regards to the implementation of either NCODA or the simpler technique presently being used in the North Atlantic near real-time system. The computer resources necessary to run the system will play a crucial role in determining which system will be affordable to use.

b) **Data management**

The HYCOM Data Distribution System (HDDS) effort (S. Hankin, A. Srinivasan, P. Cornillon) has had to address a number of distinct but coupled tasks: receiving model outputs from data providers (still principally NRL at this point in the Consortium lifecycle); converting between formats as needed to meet data serving needs; providing data subsets to internal HYCOM Consortium modelers for purposes of forcing downscaled (coastal) models; providing access to HYCOM outputs for interdisciplinary science and education needs in a variety of formats; providing an on-line environment to assist with validation and intercomparison of model runs. Major accomplishments of the first two years of data management efforts within the HYCOM Consortium are presented below in bullet form. This work has closely followed the Data Sharing Plan put forward in the original proposal. A significant item in that work plan was to prototype and test techniques for on-demand data sharing that involved on-the-fly regridding of hybrid-Z coordinate (3D) fields. While those techniques were successfully implemented, it was learned (to no great surprise!) that the performance of the hybrid-Z regridding was insufficient to be offered as an on-demand service. On-demand hybrid-Z regridding will therefore only be proposed for the relatively small (a few time steps) real-time forecast fields.

- Basic HYCOM data pipeline and data serving capabilities implemented
    - "Operational" pipeline of data transfer and format conversion as necessary between NRL and RSMAS
    - On-line browsing, visualizations on all axes and planes, and custom subsetting with LAS
    - FTP site delivering standard outputs and by-special-arrangement custom subsets
    - Access to both individual files and aggregated (long time series) model outputs via OPeNDAP

- Development of the initial HDDS file management strategy, in which files are stored at RSMAS in netCDF format (because this is most popular with most users), and converted back into ".a" and ".b" formats as needed through an on-demand LAS request.

- Direct LAS serving of curvilinear , HYBRID coordinate data prototyped, tested
    - On-the-fly conversion to rectilinear XY coordinate system
    - On-the-fly conversion from hybrid to native Z coordinates (see discussion in the Overview section above)

- A seamless segue from on-line browse in LAS to deeper analysis with desktop applications, including IDL, Matlab, Ferret, GrADS provided through on-demand script outputs which establish an OPeNDAP connection between the application and the data.

- On-the-fly, server-side transformations of data (including regridding, averaging, extrema, …) through the OPeNDAP protocol using the Ferret Data Server (FDS)

- Rudimentary analysis capabilities (averaging, extrema, simple expressions, …) for general users through the (LAS) web browser interface

- Initial data providers on line and participating in the HDDS (note that during the first two years only NAVO has been a major data provider)

- Initial data users into this framework (Bryan Blanton at UNC was identified and has been helpful as a "test" client of the system. HYCOM data is being made available through the US GODAE model intercomparison site. The HYCOM Pacific model domain is being introduced into the Pacific Region Integrated Data Environment (PRIDE) (under separate funding).

- Enhancements to LAS in support of HYCOM
  - A seamlessly integrated "batch" output capability to support the delivery of output subsets too demanding to provide on-demand
  - A highly customizable framework for presenting collections of model runs (and related climatologies, etc.) as browsable, searchable hierarchies.
  - Automatic generation of a Unidata THREDDS catalog (see http://my.unidata.ucar.edu/content/projects/THREDDS/index.html), to further integrate the HDDS into the community-wide model and data distribution framework.

- Enhancements to OPeNDAP in support of HYCOM

c) **Boundary conditions for regional/coastal models**

The horizontal and vertical resolution chosen for the above forecasting systems marginally resolves the coastal ocean (7 km at mid-latitudes, with up to 15 terrain-following (σ) coordinates over the shelf), but is an excellent starting point for even higher resolution coastal ocean prediction systems. The resolution should increase to 1/25º (3-4 km at mid-latitudes) by the end of the decade. An important attribute of the data assimilative HYCOM simulations is therefore the capability to provide boundary conditions to regional and coastal models. In order to increase the predictability of coastal regimes, several partners within the HYCOM consortium are developing and evaluating boundary conditions for coastal prediction models based on the HYCOM data assimilative system outputs. As stated above, coupling HYCOM to other models, such as the NCOM or ROMS, has already been demonstrated, while coupling of HYCOM to unstructured grid/finite element models is in progress.

B. Blanton is presently evaluating the ability of the near real-time HYCOM nowcasts and forecasts at providing accurate initial and boundary data for limited-area, regional simulations in the South Atlantic Bight (SAB) region of the eastern US coast. The regional system consists of a nested regional- and limited-area high-resolution finite element model with physical forcing such as tides, river discharge, etc. The finer grid resolution is needed to properly model the SAB since the 1/12º North Atlantic HYCOM cannot be expected to include all forcing and physics relevant at the regional scale. The quasi-operational regional-scale modeling system for the University of North Carolina (UNC)-SAB (NOPP-funded SABLAM, SEACOOS, Blanton, 2003) uses the finite element coastal ocean model QUODDY (Lynch et al., 1996). Terrestrial buoyancy inputs to the continental shelf, strong tides, and a vigorous western boundary current contribute to the complexity of this region. To address the simulation of density-dependent dynamics, the UNC-SAB modeling system is nested within the HYCOM GODAE near real-time system. Boundary and initialization data for the SAB regional-scale model are obtained from the above mentioned HYCOM GODAE Live Access Server and mapped to the finite element regional model domain. The latest HYCOM nowcast/forecast sequences are routinely acquired to initialize the regional-scale SAB model simulation. (A hindcasting mode allows historical simulations that include the limited-area, estuary resolving system.) Figure 1 shows the sequence of nests for the UNC-SAB system. The HYCOM model outputs are interpolated to the regional-scale domain (middle panel, Figure 1), with care being given to accuracy, rather than conservation, of the fields. Differences in bathymetry and coastal wall definition between the two modeling systems prevent from satisfying both accuracy *and* conservation. For each forecast, the system spins up the regional tides for 5 model days, with the density field held fixed. The atmospheric (buoyancy and momentum) and river fluxes are turned on.The timing is synchronized such that the fluxes are active for 1 day at the time the HYCOM fields are valid.

Evaluation of the near real-time HYCOM outputs relative to available observations in the SAB consists of comparisons to CODAR surface velocities in the Cape Hatteras region, NOS water levels along the coast, and mid-shelf temperature from the SABSOON observational network. A recent CODAR installation in the Cape Hatteras region is capturing surface flow details on the continental shelf as well as the western-most edge of the Gulf Stream in this region. The first 2 EOFs of the HYCOM mixed layer speed and CODAR observed speed show that the mean path mode is clearly the largest (as it should be), accounting for 97% and 71% of the HYCOM and CODAR variance, respectively. The second mode represents the variance associated with the separation variability of the Gulf Stream at Cape Hatteras. For this mode, both the observations and HYCOM show a similar pattern and both account for much less of the variance. Variability in observed coastal water levels is generally attributable to tides and wind-stress driven and other lower frequency fluctuations (deep-ocean contributions to shelf-wide sea level). In the SAB, tides account for at least 90% of the total water level variability. Figure 2a shows *subtidal* coastal water levels for 2 stations in the SAB. Lower-frequency, seasonal-scale variations are well captured by HYCOM, a reflection of the quality of the wind stress source (NOGAPS). Weather-band fluctuations are also reasonably well represented. Observations of *in situ* water fields (salinity, temperature) are comparatively less available in the SAB. The SABSOON observational network, situated on the Georgia continental shelf, has been making routine and real-time observations of water properties for 3 years. Figure 2b shows the observed SABSOON R2 near-surface temperature and the HYCOM mixed later temperature. The HYCOM mixed layer covers most of the water column vertical grid in this region. The RMS error between the signals (where they are both available) is 1.4 deg C.

The hindcast mode of the UNC-SAB system is being used to evaluate the HYCOM best-estimate archive of solutions as best-prior-estimates of the density field in the SAB. The summer of 2003 exhibited strong cooling along the eastern US coast (Figure 2b), attributed to a variety of coincident environmental conditions. Initial results from this hindcast show that upwelled, cool water is present in both HYCOM (along the Georgia/Florida coast) and in the higher-resolution limited-area model. The cross-shelf temperature gradient in the limited-area solution evolves quite differently and the veracity of this is being investigated. This summer period had larger-than-normal rain fall in the Southeast US, and consequently increased river discharge of relatively fresh water. The input, and subsequent poleward advection of the river discharge is seen in the limited-area model surface salinity snapshot (not illustrated).

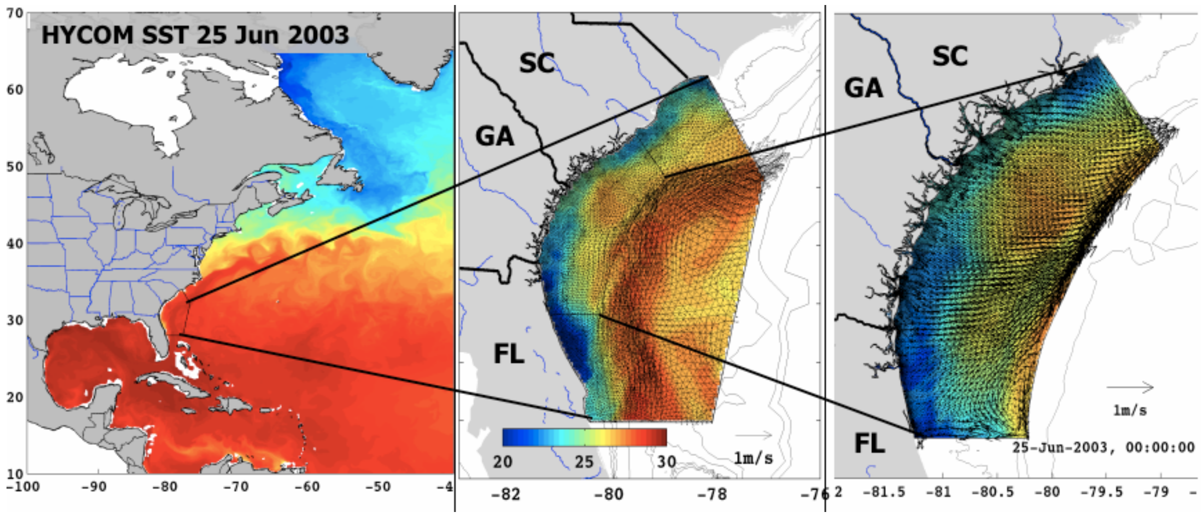

Figure 1: UNC-SAB modeling system sequence that nests the regional-scale QUODDY implementation (middle) within the 1/12 deg operational HYCOM-GODAE model (left). The limited-area QUODDY implementation (right) includes the estuary and tidal inlets along the Georgia/South Carolina coast and extends to the shelf-break.

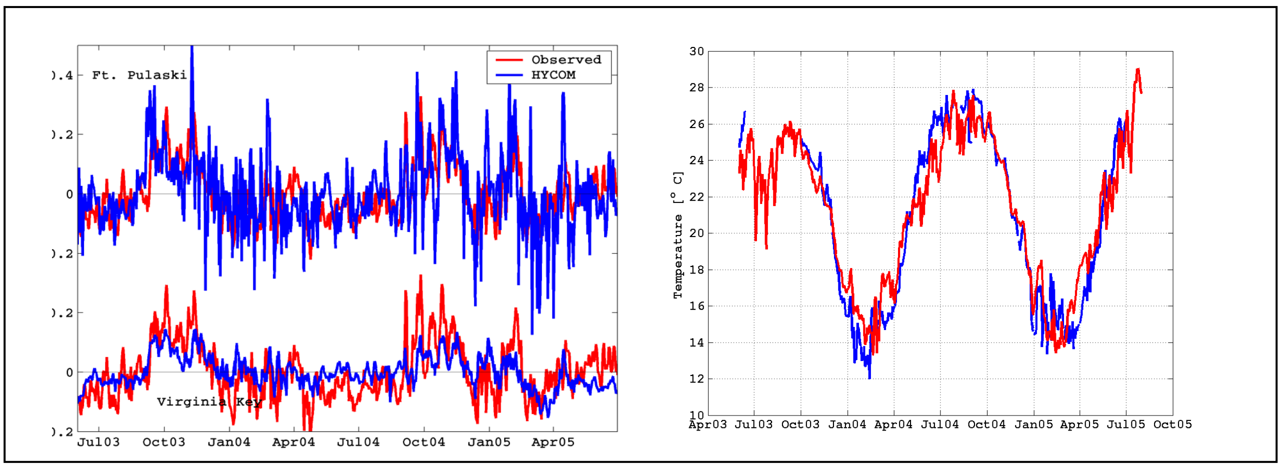

Figure 2: (left) Water level comparison for two stations in the SAB. Daily HYCOM best-estimate water levels (blue) and observed NOS water levels (red) are shown for Fort Pulaski GA (top) and Virginia Key FL (bottom). The two stations are arbitrarily offset for clarity; (right) Observed, near-surface temperature (blue) and HYCOM mixed-layer temperature (red) for the SABSOON mid-shelf station R2. The RMS error at this location is 1.4 deg C. The strong cooling of the SAB continental shelf during summer 2003 is seen in the HYCOM temperature.

A West Florida Shelf (WFS) model based on the Regional Ocean Model System (ROMS) was also nested by A. Barth (USF) in the 1/12° North Atlantic HYCOM forecasting system. The nesting procedure is as described above and the model implementation is tested against in situ data over a one-year hindcast simulation. Results are compared qualitatively to sea surface height and quantitatively to in situ temperature and velocity measurements on the shelf. The nesting of the regional model improves the performance on the shelf. Tides are in the process of being added. J. Wilkin (Rutgers) is also evaluating the impact of the boundary conditions provided by 1/12° North Atlantic HYCOM forecasting system in Northeast North American shelf model using ROMS (see http://marine.rutgers.edu/~wilkin/wip/nena/wilkin_hycom_poster_2005.pdf for a summary).

IMPACT/APPLICATIONS

Three-dimensional (3D) depiction of the ocean state at fine resolution in real-time and provision of boundary conditions for coastal and regional models in the context of the Global Ocean Data Assimilation Experiment (GODAE).

TRANSITIONS

None.

RELATED PROJECTS

This is a highly collaborative NOPP project with 24 partnering groups as listed above. Additionally, the project is receiving grants of super computer time from the DoD High Performance Computing Modernization Office.

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